Comparison of three inventory protocols for use in privately-owned plantations under transformation to Continuous Cover Forestry

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Abstract

Interest is growing in Continuous Cover Forestry (CCF) as a management approach among private forest owners in Ireland. Developments in forest policy are directed at promoting CCF as a means of enhancing forest resilience, sustaining forest production and delivering diverse ecosystem services. In 2019 the Department of Agriculture, Food and the Marine (DAFM) introduced a new pilot funding measure to support the adoption of CCF management in suitable private forests. Currently the area of forest under CCF management is relatively small (estimated at around 1% of the total forest area) and several barriers to wider adoption have been identified. These include the lack of a simple template for the transformation of planted forests to CCF and a monitoring protocol with known inventory costs and outputs. In this study three inventory protocols were compared in terms of their ease of use, the types of data outputs and cost effectiveness in a forest stand at an early stage of transformation to CCF. These protocols were compared to a complete enumeration approach. The inventory protocols being tested were developed by the UK Forestry Commission (FCIN45), a group of French and Belgian researchers (VISUAL) and the Irregular Silviculture Network (ISN). Results indicate that by using modern technology and careful design, a cost-effective inventory protocol can be implemented to collect information of sufficient accuracy to inform management decisions. Advantages and limitations of each protocol are discussed. The ultimate outcome would be the development and adoption of a common inventory and monitoring approach to enable private owners to critically compare stand management and performance. This is essential to support and guide forest managers and forest owners during the transformation process.

Keywords: *Continuous cover forestry, transformation, irregular structure stands, forest inventory, inventory costs.*

Introduction

Continuous Cover Forestry (CCF) can be an attractive management option for owners of private forests as it supports regular and profitable timber production, reduced establishment costs by exploiting natural regeneration, while retaining, in the long

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term, key ecological functions associated with natural woodlands (Ní Dhubháin 2003, Helliwell and Wilson 2012, Sanchez 2017). CCF can be achieved using many silvicultural systems, from shelterwood to *selection-irregular* silviculture (Ní Dhubháin 2003). This study will focus on the latter. Irregular silviculture aims to develop balanced irregular forest structures and promotes the use of complementary species and natural regeneration. As it makes use of natural forest processes, it is also known as Close-to-Nature Forest Management (Puettmann et al. 2015). In particular, it can offer increased ecological resilience compared with monoculture plantations (Brang et al. 2014) and delivers a wide range of timber products and ecosystem services, including the conservation of soils, water resources and wildlife habitats (Reynolds 2004, Ireland et al. 2006, O'Hara 2014).

Recent research and best-practice guidelines promote a process of "progressive transformation" as the most effective pathway to securing the targeted irregular stand structure for CCF management (Poore 2007, Poore and Kerr 2010, Poore 2016, Süsse et al. 2011, Price and Price 2006). Generally, this involves crown thinning of uniform plantations to promote high quality individual trees and introduce structural diversity. Progressive transformation of plantations to irregular stands moves through four well-defined stand development stages (Schütz 2001) (Table 1). In some ways, these stages mimic the process of natural forest succession (Oliver and Larson 1996, Schütz 2001, Poore 2007, Cameron and Hands 2010). At each stage, management interventions aim to select and promote future crop trees, improve breeding of forest stock and to ensure adequate levels of recruitment of desired species within each structural component in the stand (from seedlings to mature trees).

Unlike the clearfell and uniform shelterwood systems where all trees in the stand are managed towards a uniform target size to be harvested over a relatively short period of time, irregular silviculture aims to create a conveyor belt of timber where high quality stems within the stand reach maturity at different times, and sawlog is harvested continuously, at regular intervals, with recruitment of younger trees to the canopy without a loss of forest habitat at any stage (Sanchez 2017). The focus on individual tree selection and management enables the forester to concentrate stand increment on high quality stems resulting in high-value increment (Lähde et al. 2001, Sterba and Zingg 2001, Price and Price 2006, Süsse et al. 2011). The system ultimately aims to create a regular, steady income for the owner while minimising costs (Purser et al. 2015).

In Ireland, a growing number of private forest owners are interested in CCF (Vítková et al. 2013). This is being supported and encouraged by a pilot funding measure dedicated to CCF management in forests and launched by the Department of Agriculture, Food and the Marine (DAFM) in 2019 (Forest Service 2019). Of the 226,000 ha of grant-aided private plantations in Ireland, 59.4% are less than 20 years of age, and 37% are between 10 and 20 years (Forest Service 2018a) at first or

Table 1: *Summary of developmental stages in the transformation process to an irregularly structured CCF stand.*

Stage	CCF transformation stage	Natural forest development stage	Activities
1	Preparation thinning	Stem exclusion (pole-stage)	• removal of poor-quality stems to promote selected quality stems • selective thinning to improve tree stability while minimising disruption to stand stability (i.e. early first thinning and frequent light thinning to follow) • promote patchiness and suitable species diversity to assist with irregular structure development
2	Reduction of stand basal area to promote natural regeneration	Understory re-initiation stage (natural regeneration)	• increase timber removal to reduce basal area to facilitate the development of cohorts of regeneration of suitable species (and/or under-planting if needed)
3	Structural development	All sizes (beginning of "old growth" stage)	• using selective felling, shape the stand structure towards a desired broad diameter classes distribution, species distribution and desired standing volume • remove max 20% of the stand BA at each intervention and in general no more than the increment since previous intervention
4	Structural maintenance	All sizes ("old growth" stage)	• when a desired functioning structure is achieved (sustained yield, rejuvenation and ecosystem resilience) maintain the structure by removing the increment mostly from large trees. • manage disturbances (i.e. wind-blow) • review long term inventory learning of ecosystem functioning

second thinning stage; which makes optimal timing for initiating stand transformation (Mason and Kerr 2001, Cameron 2002, Wilson et al. 2018). While transformation from conventional plantation to irregular stand structure is not always possible, as elevation and soil quality could undermine forest wind stability during the transformation, the coming decade offers a considerable opportunity to initiate transformation in many suitable plantations. However, clearfelling remains the dominant silvicultural system and further work is required to overcome barriers to wider adoption of CCF among private forest owners in Ireland.

Several barriers to the wider application of CCF in Ireland were identified by Vítková et al. (2014) and include: a perception that CCF is too complex, a lack of existing working examples, and a lack of models for timber yield forecasting in irregular-structured, mixed-species stands. The lack of a transformation template and a monitoring protocol, with known costs and data outputs, are also recognised as major limiting factors (Vítková et al. 2014). Of particular importance is the control of stand basal area and its distribution between broad DBH classes across species. Yet many forests under transformation to CCF lack a permanent inventory that provides this and other quantitative information (Kerr et al. 2002). This limits an evidence-based approach to CCF management (Süsse et al. 2011); the manager's task is then made more difficult in terms of measuring silvicultural progress and deciding on the most appropriate stand interventions.

Inventory and monitoring protocols for CCF must incorporate several discrete elements to fully account for the structural complexity and dynamic processes associated with irregularly structured stands. These include basal area and stocking distribution between tree social classes and species; quality and distribution of selected trees; vitality and stability of selected trees; presence of sufficient seedling/sapling/pole cohorts for canopy recruitment (Süsse et al. 2011). Basal area increment is a proxy for volume increment. Increment will also become progressively important to measure the productivity rate of the stand and to facilitate the generation of a timber forecast from stage 2 onwards. This can be assessed by comparing data between two inventories. In early-stage transformation, volume estimates can be derived using basal area and form factor tables/charts used for uniform plantations (Deffee 2015, Poore 2007). As the stand advances into stage 2, it is likely that stand volumes will progressively diverge from standard tables. At this stage there will be a need for adopting new methods for assessing standing volume in irregular stands. This problem can be solved in several ways, e.g. by applying tables in use in Europe for irregular stands, using the volume/basal area ratio (VBAR) (Deffee 2015, Poore 2007) or using single-tree volume equations as developed by the National Council for Forest Research and Development (COFORD) though the TREEMODEL project and applied to the National Forest Inventory in 2015 and 2017 (Forest Service 2018b).

Ideally, an effective inventory protocol for CCF should facilitate the setting of management objectives, be affordable and be relatively user-friendly with respect to monitoring the transformation process (Sterba and Ledermann 2006). It should also provide, over time, increment data from which reliable stand-level roundwood production forecasts can be derived to guide management interventions. Several organisations have developed inventory and stand monitoring protocols for CCF management, including the Forestry Commission (Kerr et al. 2002), forest researchers in France and Belgium (Visual project) (Lejeune et al. 2005, Sanchez and Van Driessche 2016), and the Irregular Silviculture Network (ISN 2017). The ISN protocol has been adapted by a group of foresters in Ireland and the UK from methodologies originally devised by the *Association Futaie Irrégulière* (Süsse et al. 2011). Each of these protocols defines an optimal sampling intensity and provides key statistics on stand attributes that include basal area, size frequency distribution, species composition and density of natural regeneration. In the case of the ISN protocol, data on stem quality and habitat potential can also be recorded. The availability of a transformation roadmap derived from a simple and effective stand inventory would provide a valuable tool to guide and instil confidence among managers and owners of private forests interested in adopting irregular silviculture (Vítková et al. 2014).

Most inventory protocols cited in the literature for irregular stands are designed for research purposes, are resource intensive and more suited to large organisations (Süsse et al. 2011, Cameron and Hands 2010). No recent studies have assessed the potential of alternative inventory protocols relevant to the transformation to CCF of private planted forests in Ireland, where relevant information (including stocking, species and DBH distribution) must be collected in an efficient manner to minimise costs. Therefore, the primary objective of this study was to compare three established inventory protocols (i.e. FCIN45, VISUAL and ISN) in terms of the types of data outputs, efficiency of data collection and inventory time-costs. Each protocol was assessed with reference to CCF management in private forests and their effectiveness as a tool for monitoring changes in stand structure, regeneration and productivity over time. Control of management costs is a key consideration for private forest owners, and each protocol was measured in terms of time-cost to deliver key inventory data, under common site conditions. As this study focuses mainly on monitoring the restructuring of plantations through late stage 1 and early stage 2, volume and increment calculations will not be discussed in detail.

Methods and materials

Inventory Protocols

In total, four inventories were undertaken at the study site. A 100% enumeration of the research site was necessary as a basis to compare the performance of each of the selected inventories. Details of each protocol are as follows and are summarised in Table 2.

100% Enumeration

Complete enumeration, also known as "*Method du Controlle*" or Check Method, was introduced in Switzerland and continental Europe during the 19th century to monitor forest structure and growth in irregular stands (Knuchel 1953, Poore 2004). It involves recording diameter and species, plus other relevant data, for each tree within a stand

Table 2: *Comparison of execution protocol for FC45, VISUAL and ISN.*

	FCIN45	VISUAL	ISN
Plot type	Eight-meter fixed-radius.	Combination of a fixed 15-m radius plot and point sampling using relascope.	Combination of fixed 10-m radius plot and point sampling but measuring DBH for trees and poles within limiting distance from the plot centre.
Plot set up	Place vertex transponder in each of the plot centre. Place markers at north, south, east, west 8 m from centre using Vertex to measure distance. The markers will serve as plot demarcation.	Place vertex transponder in each plot centre. Demarcate a circular plot by placing 4 markers at north, east, south and west, 15-m from plot centre. Measure distances with Vertex. The markers serve as rough plot demarcation.	Place vertex transponder in each plot centre. Demarcate 10-m circular plot by placing 4 markers at north, east, south and west 10-m from plot centre. Measure distances with Vertex. The markers will serve as rough plot demarcation.
Tree sampling	Starting from the north marker and moving clockwise measure one DBH (east-west direction) for each tree, record species, visually assess crown and stem class and measure height of the largest DBH tree in the plot.	Take a relascope sweep using prism basal area factor 2. For each tree, visually estimate which broad diameter class it belongs to and enter relascope count in the appropriate column in a pre-prepared spreadsheet form using the datalogger. Do not count poles (stems <17.5 cm DBH). Starting a second time from the north marker and moving clockwise within the 15-m fixed plot for each tree, record species, visually assess crown and stem class and measure height (Vertex) and DBH of the largest DBH tree in the plot.	Starting from the 0 grads marker and moving clockwise measure DBH for each medium and large tree within limiting distance. At the selected basal area factor (BAF) 2, the max distance (m) for a tree to be included can be calculated by dividing the tree DBH (cm) by 2.83. Also, the Vertex has a BAF inbuilt function that instantly calculates and displays the minimum diameter each tree needs to be (at the selected BAF and measured distance) to be included. For each "in" tree, record the following: distance (Vertex) and bearing (Suunto), two DBH (first one parallel with the bearing, second one perpendicular to the bearing), species, visually assess crown and stem class and measure height of the largest DBH tree in the plot. All small trees (DBH 17.5-27.49 cm) are to be measured in the same way as medium-large trees but within the fixed-10-m radius of a sub plot.
Pole sampling	In the same fashion as for trees, measure all poles DBH, record species and note any PFT (Potential Future Tree) pole.	With a third clockwise movement, in the 15-m plot, count all poles by species and note any PFT (Potential Future Tree) pole.	Together with small trees within the 10-m subplot, measure for all the poles the distance from centre, bearing and one DBH (perpendicular to the bearing). Record species and note any PFT (Potential Future Tree) poles.
Seedling/ sapling sampling	With a clockwise movement count, for each species, all seedlings and saplings present in the 8-m radius plot.	In the 15-m radius plot carry out "walk-over survey" and visually assess all seedlings and saplings by allocating density classes for each species.	Starting from the 0 grads marker and with a clockwise movement, for all species count all seedlings and saplings in the three 1.5-m radius sub plots (see Figure 4).

and it is repeated at regular intervals. Due to the time and resource requirements of complete enumeration, alternative statistical sampling methods have been widely adopted.

Protocol 1: FCIN45

This sampling protocol was developed by Kerr et al. (2002, 2003) for use in plantations in transformation to CCF, hereafter called "FCIN45". It proposes a systematic grid of fixed area circular plots (either permanent or temporary) in order to capture species, tree DBH classes, natural regeneration and comes with associated MS Excel-based software to compute and compare current DBH distribution against an "ideal" reverse J-curve distribution. Stems in excess of ideal distribution can then be identified for future removal.

Protocol 2: VISUAL

This sampling protocol was devised by France and Belgium forestry researchers (Lejeune et al. 2005, Sanchez and Van Driessche 2016) for repeated surveys of irregular broadleaved stands based on a combination of permanent point-sampling and permanent fixed-radius plots. Point sampling makes use of a relascope and was first developed by Walter Bitterlich in 1948 as an effective alternative to basal area estimates compared with the conventional method which involves measuring tree DBH within plots of known area (Matthews and Mackie 2006).

The novel approach of this protocol is that all variables are visually assessed using only a relascope, pre-determined dimension-classes and the operator's judgment. Basal area readings for trees are visually split between species and broad diameter classes, poles are counted, stem quality is visually graded and natural regeneration allocated into visual density classes. This protocol will be hereafter called "VISUAL".

Existing trials (Lejeune et al. 2005) indicate that, given a trained operator, the deviation between 100% enumeration and visual inventory, for measured variables, is reasonably low (around 10%). VISUAL comes with Excel worksheets that compute and compare basal area values for broad diameter classes against target values for different stand types. This gives an indication of future removals required to achieve a desired broad diameter-class distribution (Table 3).

Protocol 3: ISN

This protocol, launched in 2017, was proposed by a group of UK and Ireland researchers and practitioners under the name "Irregular Silviculture Network" (ISN) as an inventory and valuation tool for permanent irregular stands. This protocol will be hereafter referred to as "ISN". The protocol is intended for use by foresters and represents a simplified version of a more complex "AFI" protocol commonly used for research across Europe

Table 3: *Information gathered in the VISUAL spreadsheet to measure stand structural balance (Sanchez and Van Dressche 2016).*

Species	**Basal area** (m^2 ha^{-1})				
	Small trees	**Medium trees**	**Large trees**	**Very large trees**	**%**
Birch	3.90	0.85	0.15	0.00	28.3
Oak	0.70	0.95	2.45	0.95	29.2
Scots pine	2.65	2.05	0.45	0.00	29.8
Larch	0.00	1.00	0.10	0.00	6.4
Rowan	0.70	0.40	0.00	0.00	6.4
Total					100.0
Total BA (m^2 ha^{-1})	7.95	5.25	3.15	0.95	17.3
Basal area %	46	30	18	5	
Total typology	Overrepresented	Optimal	Underrepresented		
Ideal basal area structure	Small trees 10-25%	Medium trees 30-50%	Large + very large trees 45-75%		

to monitor performance of irregular stands for a range of forest types (Süsse et al. 2011). ISN uses a combination of point sampling and fixed-area permanent plots for measuring large and medium trees, poles and seedling classes. Within the point-sampling "plot", however, instead of a relascope sweep (as for VISUAL) diameters are measured for trees found within the limiting distance determined by the basal area factor selected. This intends to allow for an accurate capture of DBH and basal area class distribution, especially of the more valuable larger trees (as sampling probability is proportional to size). ISN comes with a sophisticated Excel field worksheet that computes all variables and presents them in summary form, including a financial valuation. Volumes are estimated by applying single entry volume tables in use in irregular stands in Europe. Standing timber value is assessed using inventory data and price–size curves. In the first inventory, "increments estimate" and "increase in value" are provisional estimates, based on initial productivity assumptions which, as repeated inventories are carried out, will be further refined.

Study site

The stand chosen for the comparison of inventory approaches comprised 3.9 ha and is part of a 60-ha private estate in Raheen, Co. Clare (Figure 1). The forest is located at 50-70 m elevation, with precipitation of 1,200 mm yr^{-1}, has a Brown Earth soil and a moderately sheltered location. Transformation toward a CCF-managed irregular stand was initiated in 2012 to meet the owner's dual objectives of timber production and biodiversity enhancement.

The stand was selected for study for four main reasons. First, it represents a rare transformation site, under active management and at stage 2. The most recent

Figure 1: *A view of the interior of the mixed coniferous and broadleaved species stand in transformation to CCF that was used for the study.*

intervention was in autumn 2015 with the selective removal of 82 m^3 ha^{-1}, mostly large saw-log of Sitka spruce (*Picea sitchensis* (Bong.) Carr.), to favour Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.) and sessile oak (*Quercus petrea* (Matt.) Liebl.). Second, natural regeneration of desirable species was already taking place. Third, the stand was established as a mixed-conifer plantation in the 1970s with downy birch (*Betula pubescens* L.), sessile oak and other broadleaves encroaching through natural regeneration over time. This represents a likely future scenario for many currently young conifer plantations undergoing stage 1 transformation (authors' observation). Finally, the high diversity of tree species (both coniferous and broadleaved) and current stand structure were considered a suitable test for the robustness of each protocol.

Equipment

Two instruments were used during the assessment of each inventory protocol. These were selected following advice from several forestry consultants and based on a review of papers relating to irregular stand inventory (Lejeune et al. 2005, Poore 2007, ISN 2017, Süsse et al. 2011). A Haglof Vertex telemeter (Haglöf Sweden AB, Långsele, Västernorrland, Sweden) was used to measure distances up to 30 metres and tree heights (m). A manual calipers was used to measure DBH (cm). A waterproofed Apple iPad tablet computer (Apple Inc., Cupertino, California, USA) was selected for fieldwork, running a MS Excel spreadsheet (Microsoft Corporation, Redmond, Washington, USA) designed for the project. A purpose-built datalogger was too expensive for the scale of the study and would be unlikely to be used by most forest managers or private forest owners.

Baseline enumeration

The stand boundary was walked and marked with paint, and starting from the eastern corner, the DBH for each stem ≥17.5 cm was measured. Each tree was then marked with white chalk to avoid missing/re-measuring trees. A team of two, a measurer and booker, consisted of one to use the calipers and telemeter while the other entered data directly into the tablet spreadsheet.

Plot sampling design

This study used a randomised systematic sampling layout of permanent plots, as recommended for field surveying of irregular stands by many authors (Lejeune et al. 2005, Poore 2007, ISN 2017, Süsse et al. 2011). Ten plot centres were established, with each protocol being tested at each location to allow for each protocol to be directly comparable.

It was decided to use 10 measurement plots as this was considered the most compatible with all three protocol designs as they could be fitted comfortably within the stand area without causing any plot to partially fall outside the stand or for "double sampling" due to plot overlap. The plots centres were permanently marked to allow re-measuring. This is particularly important when using a point sampling approach. Trees were divided into the broad diameter classes described in Table 4. Stem quality classes and live crown classes were defined and assessed visually. Basal area factor (BAF) 2 was selected for all protocols as this was considered optimal to sample 15-20 trees per plot (stocking was estimated at c. 245 trees ha^{-1} for trees ≥17.5 cm DBH) (Forestry Commission 2015). For each protocol, the parameters measured included: species; DBH or DBH class; stem and crown class; height of dominant tree; seedlings ha^{-1}; saplings ha^{-1}; poles ha^{-1}; canopy cover %.

Table 4: *Broad tree classes used for the study (ISN 2017).*

	DBH (cm)	Height (m)
Seedling	-	<1.5
Sapling	<7.5	≥1.5
Pole	≥7.5 and <17.5	
Small tree	≥17.5 and <27.5	
Medium tree	≥27.5 and <47.5	
Large tree	≥47.5 and <67.5	
Very large tree	≥67.5	

Information about these parameters is essential to inform management to meet transformation objectives. Plot layout followed that suggested in the ISN protocol which offered the most detailed and clear execution instructions (ISN 2017). A uniform grid of permanent plot centres was overlaid on the stand map and located in the forest using a starting point. To make sure no plots overlapped or fell outside the stand area, plot centres were located at twice the limiting distance of the largest tree. Assuming 80 cm was the largest tree's DBH and the selection of BAF 2, the minimum distance between plot centres was set at 56 m, and a 28-m-minimum distance from boundaries. Plot centres were identified using several tie points taken along the middle of the forest road using a Walktax distance measurer, ranging poles and Suunto compass to measure azimuth. Metal bars were inserted below ground at plot centres to allow relocation using a map, Walktax, Suunto and metal detector. A similar methodology has been used by the AFI network where plots are routinely relocated with ease 5 years later (Süsse et al. 2011, authors' observation). The measurement protocol for FCIN45, VISUAL and ISN is presented in Table 2 and a diagram describing the layout of the ISN plot is shown in Figure 2.

Fieldwork

It took 2.5 hours for one operator to locate and permanently mark the 10 plot centres; approximately 15 minutes per point location. It took 7.5 hours for a team of two to

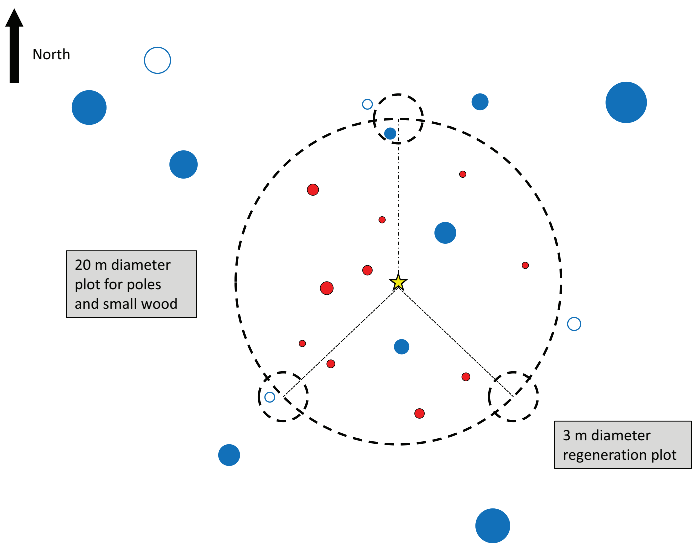

Figure 2: *Plot layout used for the ISN protocol. The red-filled circles represent small trees and poles measured within the 10-m fixed-radius plot, the blue-filled circle represent large/medium trees measured using a point-sampling approach. The three smaller plots were for surveying regeneration seedlings and saplings (ISN 2017).*

carry out enumeration. Complete enumeration was executed by two operators while the three sampling protocols were executed by one operator.

Statistical analysis

Three parameters were used to compare performance of the three protocols with results from 100% enumeration:

- stocking distribution for each broad diameter class for all species combined;
- basal area distribution for each broad diameter class for all species combined;
- variance of basal area between plots.

The first two parameters allowed the estimation of percentage deviation from true values (enumeration) by application of the Reynolds index (Re%; Equation 1). The third parameter allowed the calculation of plot variance and percentage error for the 10 plots and estimation of a likely total number of plots (N) needed to achieve precision of ±20% at 95% confidence level. This approach allowed direct comparisons of time-cost effectiveness between each protocol. Formulas for calculation of Reynold index and number of plots required for each protocol to achieve the same precision are presented below.

$$\text{Reynold index (Re\%)} = \frac{\text{sample estimate} - \text{enumeration measurement}}{\text{enumeration measurement}} \times 100 \qquad [1]$$

$$\text{Number of plots required (N)} = \frac{t^2 \times CV\%^2}{E\%^2} \qquad [2]$$

where:

E% = percentage error

t = statistical t (values of t are entered in an iterative process until N becomes stable)

CV% = coefficient of variation = $\frac{\sqrt{s^2}}{\text{mean}} \times 100$

s^2 = variance.

Results and Discussion

The study aimed to test three inventory protocols for assessing plantations at stage 2 transformation and to compare the cost effectiveness, ease of use and data outputs. It is the first study to address the needs of private forest owners engaged in transformation of planted forests to CCF in Ireland. Cost-effectiveness was measured as time-cost to deliver the same key inventory data, using the same permanent plot structure and with a precision of ±20%, at 95% confidence level. Summary of average execution time per plot for each protocol including plot centre location is presented in Table 5 and Figure 5. Results presented in Table 5 and 6 show that the VISUAL protocol was the most effective as it delivered the basic desired variables

Table 5: *Average execution times to complete a plot's measurement using each of the three protocols.*

Protocol	Plot centre location	Plot set up	DBH/ basal area	Crown & stem classes	Top height	Poles	Regeneration	Total
FCIN45	15min	2min 35s	4min 32s	3min 44s	2min 55s	3min 52s	4min 24s	37min 2s
VISUAL	15min	3min 42s	6min 55s	7min 39s	3min 7s	4min 2s	5min 30s	45min 57s
ISN	15min	5min 54s	30min 42s	7min 29s	3min 24s	14min 14s	4min 34s	81min 12s

Table 6: *Basal area distribution and stocking density results for each protocol showing Reynolds index (Re%) for each broad diameter classe and for total enumeration.*

	Small	Medium	Large	Very Large	Total
Basal area (m^2ha^{-1})					
ENUMERATION	**5.32**	**7.39**	**4.45**	**1.93**	**19.1**
FCIN45	**8.23**	**8.67**	**6.60**	**-**	**23.5**
Re%	*55*	*17*	*48*	*-100*	*23*
VISUAL	**6.8**	**8.3**	**3,6**	**1,3**	**20**
Re%	*28*	*12*	*-19*	*-33*	*4.7*
ISN	**6.8**	**7.1**	**4**	**1.2**	**19.2**
Re%	*28*	*-4*	*-10*	*-38*	*0.5*
Stocking ha^{-1}					
ENUMERATION	**148**	**75**	**18**	**4**	**245**
FCIN45	**240**	**70**	**25**	**-**	**335**
Re%	*62*	*-7*	*39*	*-100*	*37*
VISUAL	**170**	**75.4**	**13.8**	**2.8**	**262**
Re%	*15*	*1*	*-23*	*-30*	*7*
ISN	**193.9**	**74.8**	**17**	**2.7**	**288.4**
Re%	*31*	*0*	*-6*	*-33*	*18*

in the shortest time, with a low Reynold index of 4.7% and ease of execution. From Table 7 it can be seen that it would require c. 7 hours for one operator to carry out the VISUAL protocol with 9 permanent plots required to achieve a precision of ±20%, at 95% confidence level, in a highly variable stand with some challenging access (bramble patches). It is not envisaged that the typical private plantation in transformation will require more than 10 VISUAL plots (ISN 2017, Forestry Commission 2015, Sanchez 2017) or that it will present greater variability or a more challenging access than this study site. As a new inventory will be needed typically once every 4-6 years to instruct transformation management (Poore 2007, Süsse et al. 2011, Lejeane et al. 2005, Sanchez 2017), it is envisaged that the minimum time-cost for VISUAL would be in the region of 1 day for a trained operator for each felling cycle for the average private stand.

Table 7: *Plot statistics for the three mensuration protocols studied.*

	Plot	FCIN45	VISUAL	ISN
Basal area (m^{2}ha^{-1})	1	19	17	16
	2	10	18	14
	3	39	20	18
	4	42	17	15
	5	13	25	23
	6	34	30	31
	7	16	21	21
	8	17	10	10
	9	24	21	24
	10	21	21	20
	Average per ha	**23.5**	**20.0**	**19.2**
Variance		123.4	27.8	35.7
Standard deviation		11.1	5.3	6.0
CV %		47.3	26.4	31.1
E% (p=0.05)		34%	19%	22%
Plot number required at 20% error		24	9	11
Execution Time at 20% error		**14h 48min 48s**	**6h 53min 33s**	**14h 53min 12s**
Re %		*23*	*4.7*	*0.5*

100% Enumeration

Data were entered while in the forest into an Excel spreadsheet using the iPad. This approach (also adopted for FCIN45, VISUAL and ISN) provided an immediate graphic readout of the forest structure allowing for initial evaluation and saving of office time (Figure 3 and 4). It is of interest to note that the stand stocking histograms show, for the conifer portion, the typical DBH distribution expected for an even-aged plantation while, as a whole (naturally regenerating broadleaves and planted conifers together) the stand presents a “reverse J” curve DBH distribution associated with “equilibrium” irregular forests (Kerr 2002). Enumeration was only used to give baseline data and was not intended as an inventory protocol for testing. However, some consideration can still be made. Enumeration does not collect any essential information on natural regeneration, stem quality, crown classes, top height or canopy cover. It does prove to be effective and easy to execute for collecting very accurate data on species and DBH distribution. At approximately 15 man-hours to complete, it took twice the time needed for VISUAL and approximately the same as FCIN45 and ISN (Table 7) but produced a much-reduced data range. On the plus side it allowed the surveyor (in private management often the same person as the marker and forest manager) to “inspect” the site tree-by-tree and in this sense had a great stand-learning value. It is possible that for small sites (<5 ha) enumeration could be used as an inventory protocol as suggested by other authors (Poore 2004, ISN 2017) perhaps in association with transect sampling for collecting additional data.

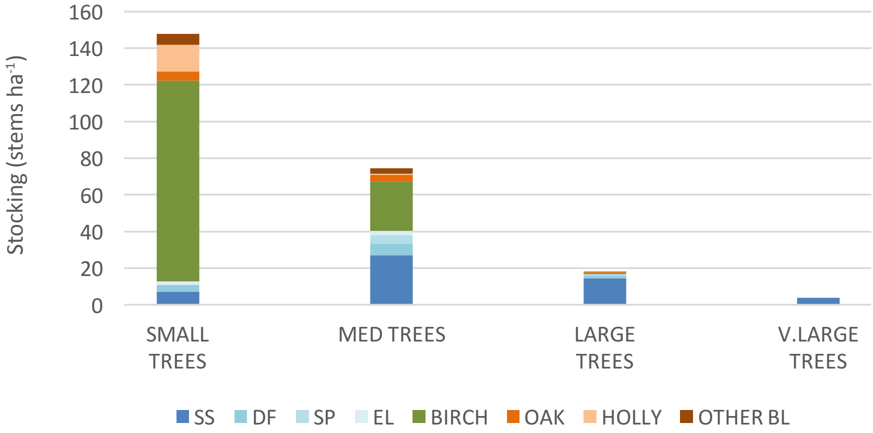

Figure 3: *Broad diameter classes distribution for the Raheen stand as measured by full enumeration.*

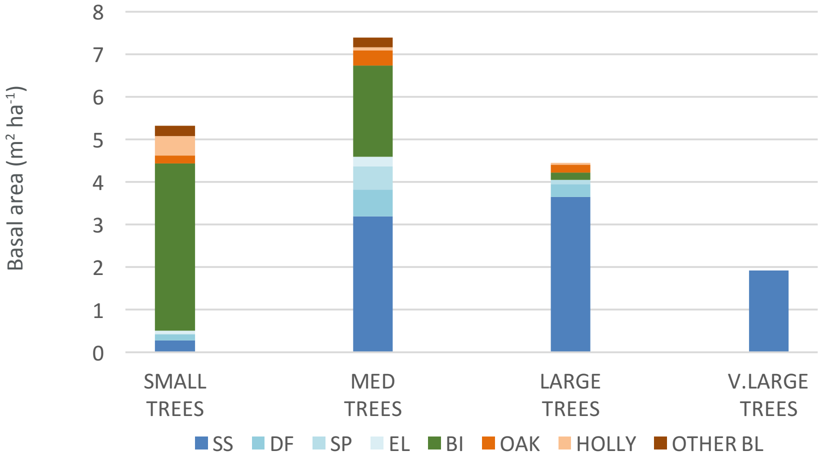

Figure 4: *Basal area distribution between broad DBH classes for the Raheen stand as measured by full enumeration.*

Protocol 1: FCIN45

Comparing execution time (at 20% error) in Table 7 and Reynold indexes in Table 6, it is evident that FCIN45 showed in this case poorer performance than VISUAL and ISN. This is probably because fixed-area plots proved less efficient at capturing irregular forest structure from stage 2 onward (Deffee 2015). In particular FCIN45 failed to capture any very large tree while it over-represented small trees in the stand (Reynold index 55%). Also, while having the same time-cost of ISN, FCIN45 offers less detailed information (no trees/poles bearing or distance from centre, one DBH only for trees) and it currently does not allow for any financial valuation.

Protocol 2: VISUAL

As mentioned, this protocol proved the most time-efficient (lower Reynold index and execution time at 20% error) (Table 6 and 7) due to the use of a combination of point sampling/fixed plot approaches and due to the use of visual classes for quickly collecting stand data. It is important to note that VISUAL and ISN shared the same sample of trees for each plot in relation to basal area (VISUAL) and DBH (ISN) as both used the concept of limiting distance to select trees. In this sense VISUAL represents a quicker approximation of the true sample value measured by ISN. For comparison in this study the difference in Reynold index between ISN and VISUAL for broad diameter classes distribution is quite low (4.2%) and shows that, while there is a large time saving associated with the visual classes approach there is only a small difference in accuracy of results between the 2 systems. This is consistent with what has been found in previous trials (Lejeaune et al. 2005). However, the fact that VISUAL did not allow the estimation of 5-cm-DBH classes like ISN means that the economic analysis potential is greatly reduced especially in relation to value increment. Stand valuation and future economic performance analysis is not currently included in VISUAL and this represents a limitation. From an execution point of view, VISUAL proved to be the easiest to execute with the most challenging aspect being the adjudication required for borderline trees. However, while this method is not precise, the results show a good degree of accuracy when considering the broad diameter classes summary. It is expected that with experience visual selection of broad diameter classes will become increasingly more accurate.

Protocol 3: ISN

This protocol achieved good accuracy with low Reynold indexes for basal area (4%) and stocking (18%), but was the most time-costly. This is to be expected as it involves additional measurement compared to the other protocols. From Figure 5 it can be seen that much of the extra time-cost was accounted for in the collection of DBH and co-ordinates of trees and poles. It can be argued that this level of detail will be very useful in time for tracking each sample tree's growth for accurate calculation of increment and monitoring each tree's development. However, it will remain to be seen if, within the scope and scale of private plantation economics, such detailed monitoring will be affordable or necessary. Also, in relation to deriving accurate increment data over successive inventories it will be essential to store, over time, accurate records for each harvest removal and to ensure that DBH and other measurement conventions are adhered to over successive inventories. The ability of ISN software to provide stand valuation and future economic performance analysis

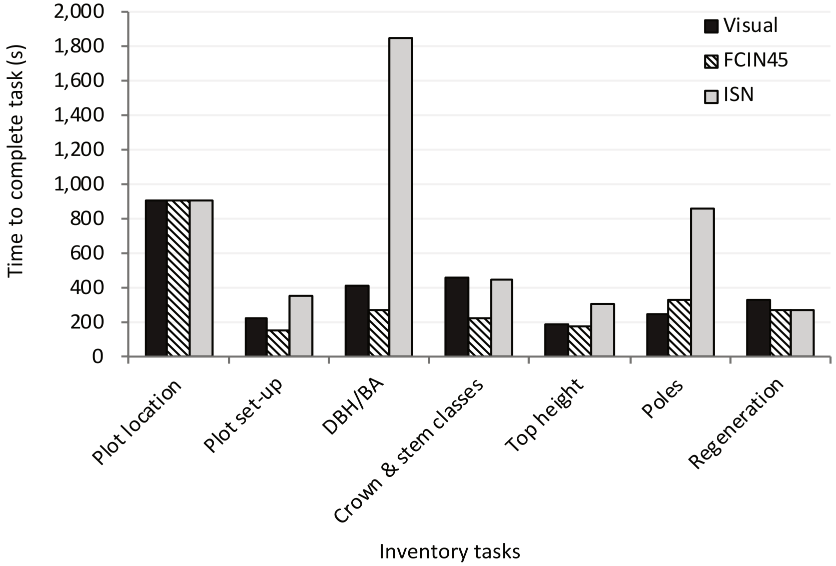

Figure 5: *Comparison of average execution time (in seconds) to locate, set up and measure a plot for each protocol.*

is certainly a very strong associated feature especially in respect of the ability to estimate annual value increment. However, this value relies at present on a number of productivity assumptions to be entered by the surveyor into the software and on single entry volume tables in use in continental Europe for irregular forest which will need further validation in Ireland. It will only be after repeat inventories that such assumptions can be verified, and a reliable value-increment figure could be produced for a range of CCF stands.

From an execution perspective ISN, as expected, was the most demanding especially for a single operator given the additional number of measurements involved. Ideally two operators would more comfortably carry out this protocol, but this would add further time-cost and reduce cost-effectiveness (Lejeaune et al. 2015, Sanchez 2017).

Conclusions

The VISUAL inventory protocol, due to the point sampling/fixed radius plot combination and the use of visual classes, resulted in the most time-efficient protocol which took the least amount of time to complete. This was estimated at 7 hours, for stage 2 to be inspected by one operator once every 4-6 years for inventory to monitor transformation of a typical privately-owned stand in Ireland. The methodology relied on some simple electronic equipment and a semi-experienced operator. In its present form it lacks analytical software to process stand volume, increment, valuation and future economic performance. This could be developed with possible integration of the broader diameter classes distribution obtained in the VISUAL protocol into the ISN software to provide for volume, increment and economic parameter computing.

In summary, VISUAL in its current form is considered suitable to the scope, scale and budget of private forests in order to monitor transformation from the beginning of stage 2.

FCIN45 would be applicable up to late stage 1. As stand transformation progresses towards stage 3, each of the structural elements emerge (from seedlings, saplings, small-medium-large trees etc.) and the value of each timber harvest increases further, it is expected that ISN might become a more attractive protocol. It is also possible that ISN could be adopted at earlier stages if detailed information was required and where additional resources were available.

Over time, the development and use of these inventory protocols should help overcome a barrier to CCF transformation by providing detailed forest structure information that a forester can work with. This will help increase foresters' confidence in the "workability" of irregular forests. Ultimately, however, it will be the actual productivity performance of transformation management that will provide confidence to owners and saw millers.

The irregular silviculture of CCF has the potential to offer private forest owners an on-going steady flow of timber/income, increased stand resilience and the opportunity for adding value to their stands. As irregular silviculture is new to Ireland it is expected that an adaptive management approach will be required. With the regular application of cost-efficient monitoring protocols, it will be possible to monitor and review at each stage, to quickly learn from practice and progressively adjust management in order to achieve stable and diverse productive forests.

This study tested protocols in one stand only. This constitutes a limitation as tests carried out in a range of stands would provide more robust evidence to draw conclusions from. Therefore, further tests are recommended for greater validation.

Acknowledgements

The authors are grateful to Coillte and William McLysaght, owner of Raheen forest, who provided access to forest sites for this study. The authors would like to thank the reviewers for helpful comments that helped improve the manuscript prior to publication. Particular thanks to Christine Sanchez (Forêt Wallonne a.s.b.l.) and Phil Morgan (SelectFor Ltd.) for their collaboration. Thanks also to Dr Alec Dauncey and Dr Mark Rayment of Bangor University for their support, as this study was undertaken by J. Spazzi as part of a MSc in Forestry at Bangor University, Wales.

References

Brang, P., Spathelf, P., Bo Larsen, J., Bauhus, J., Boncčìna, A., Chauvin, C., Drössler, L., García-Güemes, C., Heiri, C., Kerr, G., Lexer, M.J., Mason, B., Mohren, F., Mühlethaler, U., Nocentini, S. and Svoboda, M. 2014. Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. *Forestry* 87: 492-503.

Cameron, A.D. 2002. Importance of early selective thinning in the development of long-term stand stability and improved log quality - a review. *Forestry* 75: 25-35.

Cameron, A.D. and Hands, M.O.R. 2010. Developing a sustainable irregular structure: an evaluation of three inventories at 6-year intervals in an irregular mixed-species stand in Scotland. *Forestry* 83(5): 469-475.

Deffee, R. 2015. Continual inventory for irregular forest stands: experience using the AFI abbreviated inventory method on the Cranborne Estate. MSc Thesis. Bangor: Bangor University.

Forestry Commission. 2015. *Thinning Control.* Field Guide 04. Forestry Commission, Edinburgh.

Forest Service 2018a. *Ireland's National Forest Inventory 2017 Results.* Forest Service, Department of Agriculture Food and the Marine. Available at https://www.agriculture.gov.ie/media/migration/forestry/nationalforestinventory/nationalforestinventoryresultsdata/2018/Results311018.pdf [Accessed August 2019].

Forest Service 2018b. *Ireland's National Forest Inventory 2017 – Field Procedures and Methodology Covering the National Forest Inventory, 2015 to 2017.* Forest Service, Department of Agriculture Food and the Marine. Available at https://www.agriculture.gov.ie/media/migration/forestry/nationalforestinventory/nationalforestin ventoryresultsdata/2018/Field%20Procedures%20and%20Methodology.pdf [Accessed August 2019].

Forest Service 2019. *Circular 01/2019: support for Transformation to Continuous Cover Forestry (CCF) under the Element 2 of the Woodland Improvement.* Available at https://www.agriculture.gov.ie/media/migration/forestry/grantandpremiumschemes/schemecirculars/2019/Circular012019SupportforCCF230119.pdf [Accessed August 2019].

Helliwell, D.R. and Wilson, E.R. 2012. Continuous cover forestry in Britain: challenges and opportunities. *Quarterly Journal of Forestry* 106(3): 214-224.

Kerr, G., Mason, B., Boswell, R. and Pommerening, A. 2002. *Monitoring the transformation of even-aged stands to continuous cover management.* Forestry Commission Information Note 45 (FCIN45), Forestry Commission, Edinburgh.

Kerr, G., Boswell, R. and Mason, B. 2003. A sampling system to monitor the transformation from even-aged stands to continuous cover. *Forestry* 76(4): 425-434.

Knuchel, H. 1953. *Planning and Control in the Managed Forest*. Oliver and Boyd, Edinburgh.

Ireland, D., Nisbet T.R and Broadmeadow, S. 2006. Environmental best practice for continuous cover forestry. Environment Agency Science Report SC020051/SR.

ISN. 2017. Abbreviated Forest Management Monitoring Protocol Handbook. Irregular Silviculture Network, English speaking branch of the Association Futaie Irrégulière. [Unpublished].

Lähde, E., Laiho, O. and Norokorpi, Y. 2001. Structure transformation and volume increment in Norway spruce-dominated forests following contrasting silvicultural treatments. *Forest Ecology and Management* 151(1-3): 133-138.

Lejeune, P., Hébert, J., Bousson, E., Verrue, V. and Rondeux, J. 2005. L'inventaire par évaluation visuelle de grosseurs d'arbres, une alternative pertinente aux inventaires forestiers complets. *Annals of Forest Science* 62(4): 343-349.

Mason, B. and Kerr, G. 2001. *Transforming Even-aged Conifer Stands to Continuous Cover Management*. Forestry Commission Information Note 40, Forestry Commission, Edimburgh.

Matthews, R.W. and Mackie, E.D. 2006. *Forest Mensuration: A Handbook for Practitioners* (2nd edition). Forestry Commission, Edinburgh.

Ní Dhubháin, Á. 2003. *Continuous Cover Forestry*. COFORD Connects Notes Silviculture/Management No. 8. COFORD, Dublin. Available at www.coford.ie/publications/cofordconnects/ [Accessed August 2018].

O'Hara, K. 2014. *Multi-aged Silviculture: Managing for Complex Forest Structures.* Oxford University Press, Oxford.

Oliver, C.D., and Larson, B.C. 1996. *Forest Stand Dynamics*. 2nd edition. John Wiley and Sons, New York. 520 pp.

Poore, A. 2004. *Continuous Cover Forest Management of Oak/Ash Stands in the Lowlands: Stand Dynamics. Part 1: Stand Enumerations*. Available at http://www.selectfor.com/resources/articles/Article_OakAshCCFGPart1.pdf. [Accessed August 2018].

Poore, A. 2007. *Continuous Cover Silviculture and Mensuration in Mixed Conifers at Stourhead (Western) Estate, Wiltshire, UK.* Available at http://www.selectfor.com/resources/articles/Article_CCFStourheadReport.pdf [Accessed August 2018].

Poore, A. 2016. *Irregular Silviculture in the Lowlands: Transformation in Practice*. Workshop handout, Stourhead Estate, Wilthshire, England, 19-20 October 2016.

Poore, A. and Kerr, G. 2010. Continuous cover silviculture at the Stourhead (Western) Estate, Wiltshire, UK. *Quarterly Journal of Forestry* 103(1): 23-30.

Price, C. and Price, M. 2006. Creaming the best, or creatively transforming? Might felling the biggest trees first be a win-win strategy? *Forest Ecology and Management* 224: 297-303.

Puettmann, K.J., Wilson, S.McG., Baker, S.C., Donoso, P.J., Drössler, L., Amente, G., Harvey, B.D., Knoke, T., Lu, Y., Nocentini, S., Putz, F.E., Yoshida, T. and Bauhus, J. 2015. Silvicultural alternatives to conventional even-aged forest management - what limits global adoption? *Forest Ecosystems* 2: 8.

Purser, P., O Tuama, P., Vítková, L. and Ní Dhubháin, Á. 2015. Factors affecting the economic assessment of continuous cover forestry compared with rotation based management. *Irish Forestry* 72: 150-165.

Reynolds, B. 2004. Continuous cover forestry: possible implications for surface water acidification in the UK uplands. *Hydrology and Earth System Sciences* 8(3): 306-313.

Sanchez, C. 2017. *Pro Silva Silviculture: Guidelines on Continuous Cover Forestry/ Close to Nature Forestry Management Practices.* Forêt Wallone.

Sanchez, C. and Van Driessche, I. 2016. Protocole inventaire typologique. Forêt Wallone [Unpublished].

Schütz, J.P. 2001. Opportunities and strategies of transforming regular forests to irregular forests. *Forest Ecology and Management* 151: 87-94.

Sterba, H. and Ledermann, T. 2006. Inventory and modelling for forests in transition from even-aged to uneven-aged management. *Forest Ecology and Management* 224(3): 278-285.

Sterba, H. and Zingg, A. 2001. Target diameter harvesting - a strategy to convert even-aged forests. *Forest Ecology and Management* 151(1-3): 95-105.

Süsse, R., Allegrini, C., Bruciamacchie, M. and Burrus, R. 2011. *Management of Irregular Forests – Developing the Full Potential of the Forest*. Association Futaie Irrégulière. Besançon, France.

Vítková, L., Ní Dhubháin, Á., O Tuama, P. and Purser, P. 2013. The practice of continuous cover forestry in Ireland. *Irish Forestry* 70: 141-156.

Vítková, L., Ní Dhubháin, Á. and Upton, V. 2014. Forestry professionals' attitudes and beliefs in relation to and understanding of continuous cover forestry. *Scottish Forestry* 68: 17-25.

Wilson, E.R., Short, I., Ní Dhubháin, Á. and Purser, P. 2018. Continuous cover forestry: the rise of transformational silviculture. *Central European Forestry Journal* 288: 38-40.